A Method of Testing of the Plane Distribution of Anisotropy

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***Abstract*—A measuring system for investigation of the anisotropy of electrical steel is proposed. Both anisotropy of the whole sample and surface distribution of anisotropy can be determined. The sample of electrical steel in the form of a sheet was magnetized by a rotating yoke and the local value of magnetic field strength was detected. The magnetizing conditions and the sensor options are discussed. The examples of test of the grain-oriented (GO) steel are presented.**

***Index Terms*—Anisotropy, electrical steel, material testing, sensors.**

I. Introduction

The anisotropy is a crucial feature of electrical steel because it influences the most important steel parameters, such as losses. In the case of grain-oriented (GO) steel, large anisotropy results in good performances along the rolling direction. In the case of nonoriented (NO) steel, the anisotropy is undesirable because it affects the rotational losses. In practice, there are no simple and standard methods to measure anisotropy. An obvious method is to prepare a set of steel samples cut at various angles with respect to the rolling direction and test these samples individually. Shirkoohi and Arikat [1] presented results of investigations of GO steel samples by means of the Epstein method. The tests of a large number of samples is possible by steel manufacturers but not by ordinary steel users.

The use of one sheet sample to test the anisotropy is the best solution. Using the Rotational Single Sheet Tester (RSST) it is possible to test anisotropy indirectly (by changing the elliptically rotating flux) or directly, as it demonstrated Morino *et al.* [2]. The RSST systems are, in general, complicated and expensive. That is why in this work the simpler magnetizing circuit was applied. A sample in the form of a large sheet with practically negligible influence of the shape anisotropy [3] was chosen.

So far, all described methods were used to test the anisotropy of the whole sample. Meanwhile, especially in the case of the GO steel, the anisotropy changes from grain to grain. Therefore, it would be useful to investigate also the surface distribution of anisotropy. Such investigations can help in estimating the character and the quality of the texture.

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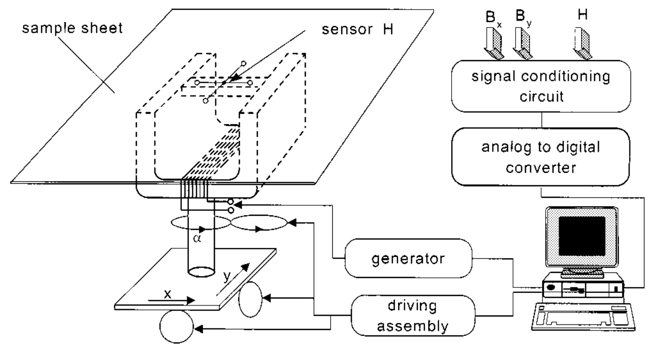


Fig. 1. The operating principle of the measuring system.

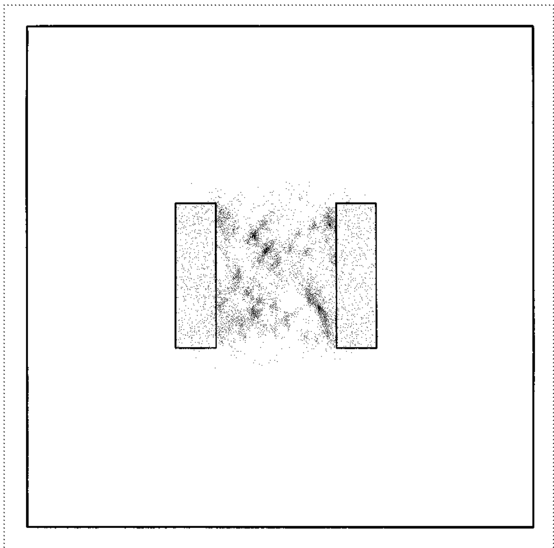
II. The Magnetizing Conditions

In earlier papers [4], [5], a measuring system for testing of the anisotropy and texture of electrical steel has been proposed. The operating principle of this system is presented in Fig. 1. Although the idea of the presented method seems to be very simple it was necessary to perform hundreds of experiments to establish the correct working conditions.

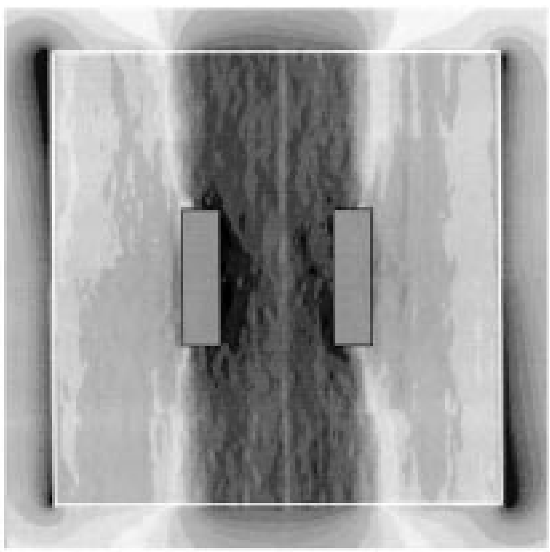
One of the most difficult to solve is the problem of uniform magnetization of the tested area. The homogeneity of magnetization is possible to obtain by using a symmetrical 2C yoke system with the magnetizing coil directly on the sheet (typically used in standard SST systems). But it is impossible to adapt such a yoke system for two-dimensional (2-D) magnetization. Usually, for 2-D magnetization a double-symmetrical 2C yoke system with excitation coils on the yokes is used [6]. The simplest solution for this problem is the change of the direction of magnetization by rotation of only one single C yoke, as presented in Fig. 1.

The results of computation of the field distribution in the magnetizing circuit shown in Fig. 1 have been presented elsewhere [7]. It was proved that for typical working conditions (GO steel magnetized along the rolling direction, NO steel magnetized in arbitrary direction) the central part of the sheet was magnetized very uniformly. But for GO steel magnetized in the hard direction of magnetization (55° and 90°) the distribution of magnetic field was very nonuniform. The experimental results of mapping of the magnetic field (the component in the direction of magnetization) are presented in Figs. 2 and 3.

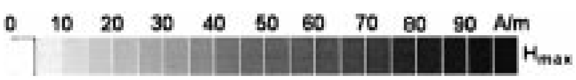
Fig. 2 shows the maps of magnetic field strength scanned above the sheet by means of magnetoresistive (MR) sensor [8]. When the sheet is magnetized along the rolling direction, practically all flux is enclosed in the area between the poles. But for the case of magnetization across the rolling direction, the flux



(a)



(b)



(c)

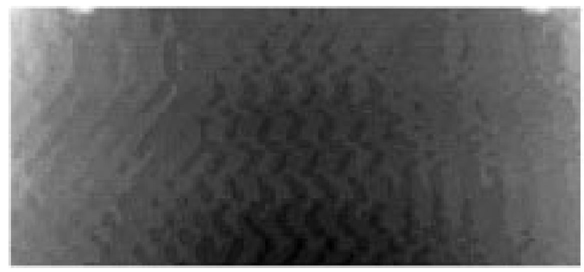
Fig. 2. The distribution of the magnetic field $H_{\max}$ in the sheet of GO steel with dimensions 30 cm $\times$ 30 cm placed on the yoke with dimensions 9 cm $\times$ 9 cm. (a) Sheet magnetized along the rolling direction. (b) Sheet magnetized across the rolling direction (fixed value of $B_{\max} = 1.3$ T).

prefers the way outside the yoke. Thus, when the steel is tested for arbitrary direction of magnetization only the central small part of the sheet can be tested. Additionally, the magnetizing conditions in the tested area should be continuously controlled during the rotation of the yoke.

III. The Measurement of B and H Values

To monitor the magnetizing conditions during the rotation of the yoke, two orthogonal B-coils were wound in the microholes at the central part of the sheet. The signal from the B-coils in the feedback circuit was used to control the amplitude and wave of the flux in the tested area.

(a)



(b)

Fig. 3. The distribution of magnetic field $H_{\max}$ (a) above the sheet and (b) under the sheet. The gray scale is the same as in Fig. 2.

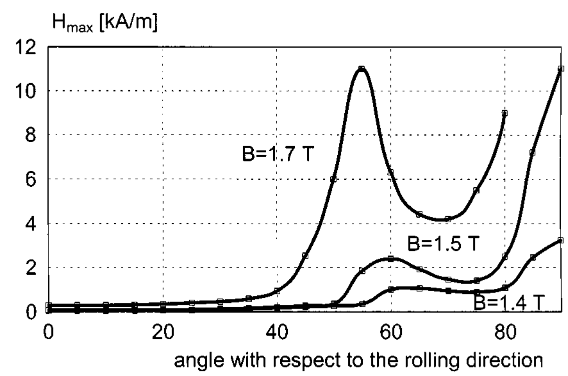


Fig. 4. The change of the magnetic field strength during rotation of the yoke (GO steel).

For fixed value of the flux density, the magnetic field strength was measured using the sensor mounted in the middle between the poles of the yoke. Beside the field nonuniformity in the sheet plane there exists also the nonuniformity in the vertical cross section. This problem was discussed elsewhere [9]. Fig. 3 presents results of investigations of the magnetic field above the sheet and under the sheet.

Because under the sheet (between the poles) the magnetic field is nonuniform, generally it is not recommended to place the sensor under the sheet [9]. For determination of the H value in the whole tested area, the H-coil sensor exhibited the best performances. Fig. 4 presents the results of investigation of GO steel sample by means of H-coil sensors placed above the sheet.

Fig. 4 presents the dependence of the magnetic field strength on the angle of magnetization. The hard direction equal to 55° (typical for the Goss texture) is detectable if the flux density is sufficiently large (larger than 1.3 T). Using a sufficiently small

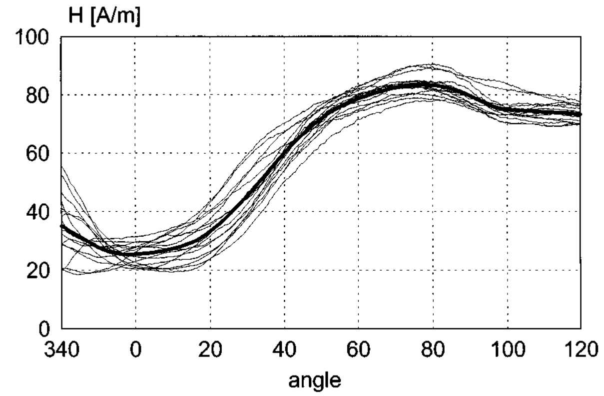


Fig. 5. The dependence of magnetic field strength on the direction of magnetization determined in 16 various points of GO steel ($B = 1$ T).

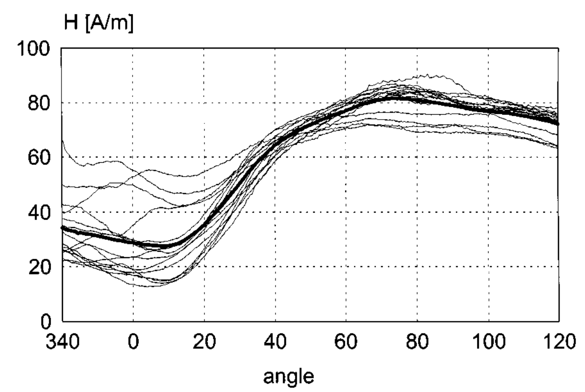


Fig. 6. The same dependence as in Fig. 5 determined for another sample.

sensor it is possible to determine similar dependence but representing local performances of the steel. This local magneticfield strength was measured using thin-film Permalloy magnetoresistive sensor with dimensions 1 mm $\times$ 1 mm.

IV. The Surface Distribution of Anisotropy

Fig. 5 presents the dependence of the magnetic field strength on the direction of magnetization determined for 16 various points of GO steel sheet. The points were distanced by 2 mm (tested area 8 mm $\times$ 8 mm).

It is almost impossible to say that each curve in Fig. 5 represents individual grain. Sometimes the tested area reaches the border between grains and even if it reaches the one grain the influence of neighboring grains is not negligible. But the spread of these curves may give information about the quality of the texture. Fig. 6 presents an example of the same test performed for another sample of GO steel. The dispersion of anisotropy in this case is much larger.

Knowing the directional dependencies presented in Figs. 5 and 6 it is possible to construct the maps representing the surface distribution of anisotropy. Similarly, it is possible to construct a map representing the distribution of the local inclination of the easy axis of anisotropy as the angle of magnetization corresponding to the minimum of magnetic field strength.

In the measuring system presented in Fig. 1, the position of the tested area was selected by x, y movement of the yoke. In this arrangement, the sensor was rotated with the yoke (under the sheet). According to results presented in Fig. 3, it is better to place the sensor above the sheet. That is why another arrangement was finally chosen: the yoke is rotated and the sensor is moved in the x, y plane above the sheet (using a separate driving assembly).

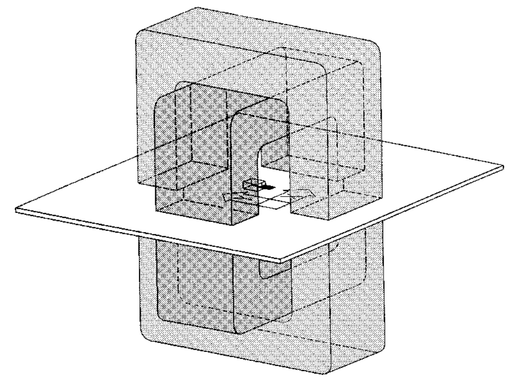


Fig. 7. The magnetizing circuit with unmovable yokes.

The results presented in Figs. 5 and 6 have been obtained using a small MR sensor. The MR sensor exhibits several drawbacks. From the results presented in Fig. 4. it is evident that to detect the hard axis of anisotropy the magnetic field strength should be larger than several kiloamperes per meter. That is beyond the typical field range of MR sensors [10]. Moreover, if an MR sensor detects the magnetic field inclined from its axis the orthogonal component influences the result [10]. That is why for tests of NO steel the MR sensor was acceptable, but for tests of GO steel better performances were exhibited with the small Hall sensor.

The one rotating yoke applied in the presented system enables the relatively simple comparison of anisotropic features of various electrical steel samples. But analysis of measurements errors [3] proved that the best solution of the problem of accuracy is to use the stationary double symmetrical yoke system presented in Fig. 7. The direction of magnetization can be varied by the change of the number of magnetizing coils turns in both yokes.

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